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# Operational experience and performance of the Belle II silicon vertex detector after the first SuperKEKB long shutdown

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## ABSTRACT

The Belle II experiment searches for beyond-the-standard-model physics using the Belle II detector and SuperKEKB collider. The silicon vertex detector (SVD) is crucial for particle tracking. After the 1.5-year shutdown from June 2022, Run 2 began in January 2024; Run 2 operation shows stable noise levels, high signal-to-noise ratios, and hit efficiency over 99%. To manage higher beam background from increased luminosity, new techniques such as hit-time selection and cluster grouping are being developed. These methods increase the acceptable level of occupancy by distinguishing hits from triggered collisions and other sources.

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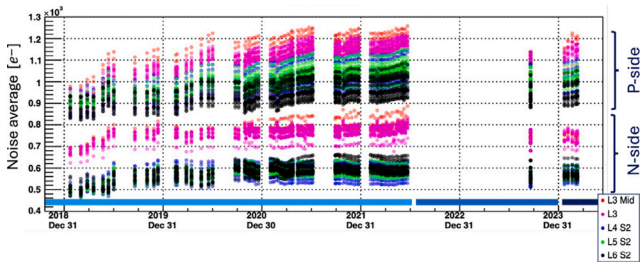


**Fig. 1.** Average noise evolution of N-side and P-side per layer from the Run 1 operation to the early Run 2.

## 1. Introduction

The Belle II experiment [1] aims to explore beyond-the-standard-model physics using the Belle II detector and SuperKEKB collider [2]. SuperKEKB, which collides 7 GeV electrons with 4 GeV positrons, achieved an instantaneous luminosity of $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by June 2022 (Run 1). The Belle II vertex detector (VXD) surrounds the $e^+e^-$ interaction point (IP) at the center of the Belle II detector. The silicon vertex detector (SVD) [3] provides charged-particle hit information to reconstruct the particle trajectories and the parent-particle decay point.

The VXD has six layers, the inner two layers consist of the pixel detector (PXD) [4], which uses DEPFET sensors, whereas the outer four layers consist of the SVD, which uses double-sided-silicon-strip-detectors (DSSDs). The DSSDs have a thickness of 300 or 320 μm. The u/P-side (v/N-side) strips measure the $r-\phi$ position ($z$ position) and have a pitch of 75 μm (240 μm) apart from layer 3, which has 50 μm (160 μm).

## 2. Long shutdown activity and Run 2 operation status

The Belle II experiment underwent a long shutdown (LS1) that started in June 2022. A key activity during LS1 was the installation of a new PXD. This involved extracting the VXD from the Belle II detector and splitting the SVD into two halves to access the PXD inside. Several checks were conducted at each step to ensure system integrity and troubleshoot potential issues. Because the power consumption of the PXD increased due to the additionally installed modules, we lowered the cooling temperature of the VXD. For the final check before the SuperKEKB beam operation, we assessed the detector readiness and alignment with cosmic rays. After LS1 concluded, Run 2 began in January 2024. We are trying to increase the SuperKEKB beam current and optimize the beam conditions to enhance the luminosity. Consequently, higher beam backgrounds are anticipated, so we continuously monitor the leakage current evolution, noise, and calibration factor changes of the SVD. During early Run 2, SVD operation was smooth, with no issues found in the related facilities.

## 3. SVD performance report from early Run 2 operation

The SVD showed excellent performance in Run 1. This section presents comparisons of noise, cluster charge, signal-to-noise ratio (SNR), and hit efficiency between Run 1 and early Run 2 to validate the early Run 2 performance. Fig. 1 shows the noise evolution during the entire operation period, including early Run 2. During Run 1, the noise levels increased by 10 to 30% due to beam-background radiation, primarily from surface damage to the SVD sensors caused by the total-ionizing-dose effect. The measured integrated dose during Run 1 is estimated to be less than 70 krad. However, noise levels increased almost to a plateau during Run 1. It is observed that the noise levels during LS1 and early Run 2 were about 10% lower than at the end of Run 1, which is most likely due to the lowered operating temperature and the annealing effect. The comparisons for cluster charge and cluster SNR show no significant differences between Run 1 and early Run 2, with cluster SNR values ranging from 13 to 30. Similarly, hit efficiency still exceeds 99%. Therefore, we conclude that the SVD performance in Run 2 is comparable to that in Run 1.

## 4. Future background rejection

The SuperKEKB beam background is expected to increase with higher beam luminosity, leading to increased hit occupancy in the SVD. Currently, occupancy is below 1%, which does not affect tracking performance. However, higher occupancy can degrade tracking performance by reducing the tracking efficiency and increasing the number of fake tracks. To address this, we will implement hit-time selection and cluster-grouping methods, which use SVD hit time to reject background hits and enhance occupancy acceptance.

The hit time is determined through waveform reconstruction from signal sampling using the APV25 readout chip [5], achieving a precise hit-time resolution of less than 3 ns with respect to the collision time. This capability enables the system to effectively distinguish off-time hits, originating from background tracks that are not associated with the triggered collision, and reject 50% of them retaining 99% efficiency on signal hits. In particular, this is achieved with a time selection that applies cuts on hit times at each sensor side $t_{u,v}$, with $|t_{u,v}| \leq 50$ ns and $|t_u - t_v| \leq 20$ ns. The newly developed "cluster grouping" method can reject background further by applying a event-by-event selection. This method groups hits by the same collision, allowing the classification of hit groups as originating from the triggered collision or from other collisions and beam backgrounds.

By applying hit-time selection and cluster grouping, we can increase the acceptable occupancy for track reconstruction to about 6% in the innermost SVD layer, allowing some safety margin for operation at the higher luminosity. Nevertheless, a proposal for a Belle II vertex detector upgrade is now also under evaluation, which considers the large uncertainty in the background extrapolation due to future machine evolution and a possible re-design of the IP [6].

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fumiaki Otani reports a relationship with Japan Society for the Promotion of Science that includes: speaking and lecture fees and travel reimbursement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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